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(54) Title: PATTERNED PART INSPECTION

(57) Abstract

A sample or input image (8) of a part to be inspected is precisely aligned (10) with a reference image derived from known good parts, so that the two images may be compared on a point-to-point (pixel) basis. This alignment is performed by matching the two images using correlation and curve fitting, and then shifting one image into alignment with the other using cubic convolution (20). Differences between the two aligned images are potential defects in the sample image. The pixel values in the difference image are reduced with a position varying threshold (53, 55) such that pixels in image areas with high intrinsic intensity variability are not incorrectly classified as defects. The remaining non-zero pixels are modified by morphological techniques (60), and then analyzed (70). The analysis may specify such measures as the size, peak value, mean, etc. of pixel groups (defects). The part is classified as good or bad comparing these measures to allowable tolerances.

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<u>Patterned Part Inspection</u>
<u>Background of the Invention</u>

This invention relates to a method and apparatus for automated visual inspection of patterned parts for defects.

5   A patterned part is a precisely formed object, such as an integrated circuit (IC), printed circuit, or printed material, with precisely structured surface detail (patterns) that can be visually inspected for defects. Integrated circuits are used as the example in describing

10   this invention, but the invention is applicable to automated visual inspection of other kinds of patterned parts.

Humans have difficulty visually inspecting patterned parts for small errors in manufacturing. We quickly see gross errors and malformations, but have trouble seeing

15   smaller errors in highly patterned objects. Instead, we tend to perceive detailed patterns as a visual texture and do not easily comprehend individual elements making up the pattern. Humans are slow in making this sort of inspection, they tire and become unreliable, and they have trouble

20   making quantitative visual measurements.

With billions of patterned parts manufactured each year and given the poor performance of humans on inspecting these parts, automated visual inspection by a machine is useful.

25   There are three general techniques for automated visual inspection of patterned parts:

1. Structural techniques characterize and measure the part's components. For ICs, such component measures might include the location and shape of traces, bonding

30   pads, and transistors. See, for example, Billiotte, United States Patent 4,881,269.

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2. Knowledge based techniques use knowledge of the design of the part to verify the correctness of the sample part. In IC inspection, Yoda et al. "An Automatic Wafer Inspection System...", IEEE Transactions on Pattern Analysis

5 and Machine Intelligence, Vol. 10, No. 1, January, 1988, describe a method of generating a comparison image and design rules from the CAD (Computer Aided Design) files used to design an IC. The comparison image can then be compared with the sample image and the design rules used to reduce

10 false positive defects.

3. Comparison techniques compare sample parts to known good parts. Differences between the sample and good parts indicate possible defects, and these possible defects are typically further processed to reduce false positive

15 defects. See for example, Ehrat, United States Patent 4,139,779.

Structural and knowledge based techniques require extensive programming to set up and require a large amount of computation during the inspection. For example, in

20 structural techniques, the location and specifications of all structures of interest must be recorded in the inspection apparatus. Even with automated techniques for set up, these methods are computationally expensive and inflexible.

25 Comparison techniques, on the other hand, are simple to set up and hence quite flexible. The visual comparison apparatus can be taught the inspection task by providing it with images of known good parts, and indicating the size and range of differences that can be tolerated. Furthermore,

30 the comparison technique can be embodied in fast and relatively inexpensive image processing hardware.

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Comparison techniques have the disadvantage that naturally occurring and acceptable shifts in part component sizes, position, and reflectivity could appear as false positive defects.

5   The construction of a reference image by averaging images of good parts is disclosed in Crane, United States patent 4,040,010 (Col. 1, lines 38-45) (Col. 2, lines 50-56).

To compare a sample with a reference image, the two
10   images must be in precise alignment. Mechanical methods are too slow and imprecise for the high speed inspection of small parts such as ICs. Electronic alignment techniques use fiducial areas on the sample and reference images to determine their position difference and then to shift the
15   images into alignment (registration).

Some known methods require the fiducial area to have special structural properties. For example, Ehrat, United States patent 4,131,879 (Col. 8, line 25, to Col. 10, line 32) describes the use of edges of letters or printed areas
20   as fiducials. Wenta, United States patent 4,880,309 describes special fiducial marks that can be etched into an IC to help locate and position the IC.

Locating the fiducial location to integer pixel positions by correlation has been done for image
25   registration--see for example Pratt, _Digital Image_ _Processing_, John Wiley & Sons (New York), 1978), pages 562-566. Other known methods use variations or simplifications of correlation. For example, Ehrat, 4,131,878 (Col. 2, lines 28-42), describes a difference
30   operation that gives the direction of shift between two images.

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        Based on the relative locations of the fiducials in
the sample and reference images, the two images are brought
into alignment by electronically moving one image. This is
commonly done by reading pixel values from one image memory
5   using an address offset that corresponds to the whole pixel
difference between the two images. See for example Ehrat,
United States patent 4,131,879 (Col. 13, lines 30-54).

        To improve the accuracy of the match and reduce
false positive defects, the image must be positioned to
10   within a fraction of a pixel. Because image memory is only
addressed in integer increments, fractional pixel values are
obtained by interpolation (see, for example Ehrat, United
States patent 4,131,879 (Col. 13, line 66 to Col 14, line
21).

15   More elaborate image registration methods have been
described, for example, Morishita, United States patent
4,644,582, but these methods are generally unnecessary when
inspecting parts with unchanging dimensions, such ICs.
Another image alignment method for detecting pattern defects
20   is to make multiple, shifted (horizontally and vertically)
copies of the reference image. Then the sample image is
compared against these shifted references and if it does not
match any of them, it is deemed defective. See for example,
Wanta, United states patent 4,803,734.

25   The two aligned images are then subtracted and the
absolute value is taken to form a difference image. The
method of subtraction and absolute value is a common and
well known technique. See, for example, Crane, United
States patent 4,040,010 (Col. 2, lines 19-24, Ehrat, United
30   States patent 4,139,779 (Col. 2, lines 9-20), Huber, United
States patent 4,311,914 (Col. 1, lines 50-59, and Yoshida,
United States patent 4,449,240 (Col. 2, lines 64-66.

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Various techniques have been proposed to reduce
false positive defects that could appear in the difference
image. For example Schmitz, United States patent 3,623,015
(Col. 2, line 8 to Col. 3, line 17) describes a threshold
5   method that dynamically adjusts to reflect the statistics of
the incoming signal. Yoshida, 4,449,240, also describes a
tracking system whereby two thresholds are updated as new
images are acquired. These two thresholds are used for the
entire image, rather than varying over the image. Crane,
10   4,040,010 (Col. 1, lines 38-56 and Col. 2, lines 19-46)
describes a threshold based on the standard deviation of the
ensemble of known good signals. Ehrat, United States patent
4,139,779 (Col. 4, lines 14-26) describe a threshold that
varies over the image as a function of intrinsic part
15   variation and is set based on the size of detectable errors.
Huber, 4,311,914 (Col. 4, lines 15-33) describes a
statistical weighting that acts as a threshold and that
varies over the image and is proportional to the intrinsic
or expected variability of the images. Schrader, 4,859,863
20   (Col. 1, lines 62-68) describes the use of a standard
deviation threshold for each pixel in the image, set by
making the threshold the three standard deviation value for
each image point. DeGasperi, United States patent 4,433,385
(Col. 5, lines 15-53) describes using within image variance
25   to set acceptance thresholds. This is different from the
across image variances (standard deviation) described in
some of the above work.

After thresholding, there still may be false
positive defects due to shifts in part pattern locations or
30   sizes. Erosion operations may be used to remove some of
these false positives. See, for example, Linger, United
States patent 4,477,926 and the paper by Yoda et al. Unlike

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many previous inventions, this invention uses grey scale
erosion rather than binary operations. Another method of
reducing false positives due to structural changes is to
smooth the potential defect image using convolutional
5   blurring followed by a threshold (see Ehrat, 4,139,779
(Col.4, line 56 to Col. 6, line 2).

The final image contains blobs of pixels that
represent errors. These blobs are measured, for example,
for size, peak value, or perimeter. The resulting measures
10   are compared with previously specified limits to determine
if the part is defective or not. See, for example Pratt,
pages 514-533.

Typical inspection schemes use binary (two valued)
images for inspection (See, for example, Linger, 4,477,926,
15   and the paper by Yoda et al.). Binary images require less
computation than grey-level (multi-valued) images but are
inaccurate in representing images. This inaccuracy shows up
as errors in edge position, increased false positives, and
reduced error detection sensitivity.

20   Summary of the Invention

The present invention performs automated visual
inspection on patterned parts at high speed and
inexpensively.

This invention uses the comparison technique because
25   of its speed and flexibility, but augments it with two
processing steps that greatly reduce sensitivity to
naturally occurring and acceptable shifts in part component
sizes, positions, reflectivity, and etc.

In general, in one aspect, the invention features
30   determining an amount of misalignment between a digitized
sample image of a patterned part and a corresponding
digitized reference image. A correlation operation is

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performed on the images to generate a correlation surface
indicative of an integral number of pixels by which the
images are misaligned. Then an analytic surface is fitted
to the correlation surface to determine a fractional number
5   of pixels by which the images are misaligned. In preferred
embodiments, the analytic surface is an elliptic parabaloid.

In general, in another aspect, the invention
features a method for inspecting a patterned part. A
digitized sample image of the patterned part is formed. A
10   convolution operation is performed on the digitized sample
image to effectively shift the digitized sample image by a
fraction of a pixel relative to a corresponding digitized
reference image. The shifted digitized sample image is then
compared with the reference image.

15   Preferred embodiments of the invention include the
following features. The convolution operation is a bicubic
convolution. Adjacent pixels of the digitized sample image
are stored at successive addresses in a memory, and
references to the addresses are adjusted to effectively
20   shift the digitized sample image by an integer number of
pixels relative to a corresponding digitized reference
image. The pixel values are grey scale.

The invention enables rapid, effective image
matching, alignment, and comparison for inspection.

25   Other advantages and features will become apparent
from the following description of the preferred embodiment,
and from the claims.

<u>Description of the Drawings</u>

Fig. 1 is a block diagram of an inspection system.
30   Fig. 2 is a flow chart of a digitizer offset and
gain adjustment procedure.

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Fig. 3a illustrates a reference fiducial pattern (squares) being correlated with one portion of a sample image patch.

Fig. 3b illustrates the result of multiple
5 correlations, where the height of the arrow indicates the degree of reference and sample pattern match.

Fig. 3c shows some examples of patterns that would make poor reference patterns (fiducials), as (from left to right) the pattern has only one edge, the pattern repeats,
10 and the pattern is noisy.

Fig. 3d, 3e, and 3f are equations and expressions.

Fig. 4a illustrates correlation peaks when the reference and sample fiducials match at a point between exact (integer) pixel locations.

15 Fig. 4b illustrates an analytic surface fit to the correlation peaks in Fig. 4a, recovering correlation peak position and hence the match position.

Fig. 5a shows the local coordinate system used for least-squares fitting of the correlation data to the
20 analytic surface.

Fig. 5b are the kernels used for computing the least-squares fitting coefficients.

Fig. 6a is a graph of the sinc function, $sin(x)/x$, for a limited range of x values.

25 Fig. 6b is a graph of a symmetric cubic polynomial function, approximating the sinc function.

Fig. 7 illustrates the reconstruction of a shifted pixel value using cubic convolution in one dimension.

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Detailed Description of a Preferred Embodiment

The method and apparatus illustrated in Fig. 1 is intended to automatically visually inspect patterned parts. Such parts do not differ appreciably in their dimensions or

5   reflectivity, except when there are defects. The method and apparatus is designed to reliably detect light reflectivity (or transmission) differences that indicate defects.

A working embodiment of this invention uses the Series 150 modular image processing hardware available from

10   Imaging Technology Inc. of Woburn, MA for the image processing functions. To simplify the description of the method, virtual data paths needed for the method are shown in the figures. These virtual data paths correspond in some cases to the Series 150 data paths. The Series 150 has

15   additional data paths and capabilities that are not shown as they are not relevant to the disclosure of the method described herein.

The inspection method is based on comparing the images derived from known good parts to sample parts,

20   reducing the resulting difference values where necessary to account for acceptable variability between parts, and then comparing the resulting values to see if the exceed preset limits. If so, the part under inspection is rejected as defective.

25   As shown in Fig. 1, a mechanical positioner 1 presents an IC (the "part") 2 to an optical system that forms an image in a camera 3 from light reflected or transmitted by the part from an adjustable light source 4. The mechanical positioner positions the part to within a few

30   pixels (digital picture elements) of a known location.

The optical system has a zoom lens 5 that is zoomed and focused to form the image of the part, and a contrast

enhancing filter 6. The optical system is normally adjusted
by the operator only at the beginning of an inspection run
to provide a focused and correctly sized image of the part
to the camera 3. An inspection run is a long sequence of
5   inspections of copies of the same part, for example one type
of IC.

The regulated light source 4 provides constant light
intensity that does not change appreciably during the
inspection run. A method to be described adjusts the image
10   acquisition electronics to best utilize the light reflected
from or transmitted through the inspected part.

The camera 3 is a high-resolution solid-state
camera that has low geometric distortion. The analog image
signal from the camera is digitized and quantized in
15   digitizer 7 and the resulting pixels are stored in a pair of
image memories 8. For high speed operation, an image is
acquired into one image memory while the system processes a
previously acquired image stored in the other memory. At
the end of processing and acquisition, the role of the two
20   memories are reversed (by switch 9). This "double buffer"
technique effectively eliminates the delay incurred in image
acquisition.

The digitizer and two image memories are part of a
single VSI-150 (Variable Scan Interface) hardware module
25   also available from Imaging Technology Inc. These
components, as well as the rest of the components in the
system, are controlled by a general purpose computer 100,
called the control computer. The control computer can set
and read any of the system's control signals and can also
30   read and write pixel values from any of the image memories.
The arrows 101 symbolize the ability of the control computer
to access any system component.

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The correct operating range for the digitizer 7 is adjusted by the control computer 100. The Gain control 701 adjusts the amplification of the analog camera signal and the Offset control 702 adds a constant value to this signal.

5 The operating range of the digitizer is automatically adjusted so that the actual quantized intensity values represent nearly the full range of possible quantized intensity values.

The method for setting Gain and Offset is shown as a

10 flow diagram in Fig. 2, and is executed as a program in the control computer.

In Fig. 2, the method starts with the acquisition (digitization) of an image (801) of an IC into image memory 8. The control computer computes (802) the maximum (max)

15 and minimum (min) pixel intensity values of this image. These values are then compared with four thresholds: upper and lower "increase" thresholds (UI and LI) and upper and lower "decrease" thresholds (UD and LD) to adjust digitizer gain and offset. The offset is adjusted by computing (803)

20 F = ((UD-max)-(min-LD))/2. If F is greater than some noise limit (804), then the offset is adjusted (805) up or down by F.

A new image is acquired (806) using the new offset value and the maximum and minimum pixel values are again

25 computed (807). If the minimum value is greater than the LI threshold and the maximum value is less than the UI threshold (808), then the gain is increased by 1 (809). If the minimum value is less than the LD threshold or the maximum value is greater than the UD threshold (810), then

30 the gain is decreased by 1 (811). The loop repeats until the minimum value is between LI and LD and the maximum value is between UI and UD (812) or until some specified number of

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iterations have occurred. The increase and decrease
thresholds are separated by a value that is at least twice
the expected digitization noise value to make sure the
process converges.

5   If the light is too dim or intense, the above
adjustment process will be unable to converge. Hence, this
process will exit after a number of iterations (not
indicated in the Figure) and warn the operator that the
light source needs adjustment.

10   The optics, camera, and digitizer are designed so
that spurious spatial frequency components are not
introduced into the sampled image. Spurious components
(aliasing) can appear when the camera analog signal is not
band-limited to below the Nyquist rate, as set by the

15   spatial digitizing frequency. To meet these requirements, a
solid-state camera with RS-170 timing and a resolution of
780 (horizontal) by 488 (vertical) sensor locations is used,
and the analog filter on the VSI-150 is set to a 3 db
roll-off at 4.2 Mhz. For RS-170 cameras, the digitizer

20   samples only 512 by 480 pixels, so the spatial sampling is
well below the Nyquist rate. Another source of spurious
spatial frequency components is if the camera's spatial
frequency response is not smooth within the sampling
bandwidth. This may happen when there are non-responsive

25   areas in between the light-sensitive elements of the camera.
           If spurious spatial frequency components are
introduced, they can decrease the accuracy of the alignment
steps described below, and this in turn can increase the
rate of incorrect defect identification (false positive

30   defects).
           The analog camera data are quantized to eight bits.
The quantized data must not be obscured by electrical and

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sampling noise. The image is digitized with enough spatial
resolution so that the defects to be detected fully cover
one or more pixels. Cameras other than RS-170 cameras may
be used to get larger image sizes. Larger image sizes may
5   be used to increase the fineness of the inspection or to
inspect larger ICs.

The light source, optics, camera, and digitizer must
be stable enough so that they need only be adjusted at the
beginning of a run. If any of these elements changes
10   appreciably during the inspection process, the inspection
may report more errors than are actually in the parts. If
the sample images are acquired under different light or
reflectance conditions than the reference image, there can
be average offsets between the images. These offsets appear
15   as constant differences when the images are subtracted, and
hence as false positive defects.

This invention uses a controlled light source that
removes this source of variability. If this is not
sufficient, there are common and well known techniques to
20   compensate for illumination intensity changes -- see for
example, Pratt, Digital Image Processing, John Wiley & Sons
(New York), 1978, pages 307-317 incorporated herein by
reference. Ehrat, United States patent 4,139,779, col. 3,
lines 13-48, incorporated herein by reference, uses a
25   neighborhood average to remove this offset (shade
correction), and Yoshida, United States patent 4,449,240,
incorporated herein by reference, describes a tracking
method to compensate for intensity changes due to aging of
the light source.

30   The image area to be inspected must not occupy the
entire image memory. Rather, a small border of inspected
pixels is required to allow the image to be shifted for

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alignment and to allow for errors in the mechanical
positioner.

There are two modes of operation of this invention:
training mode and inspection mode. In training mode the
5   invention is taught a reference image, fiducial locations, a
variability image, erosion size, and defect limits.

A reference image is a digital image formed by
averaging images of known good parts. A part to be
inspected is then compared to this reference image to
10 locate possible defects.

A reference image is started by acquiring a single
master reference. Returning to Fig. 1, an image of a known
good part is digitized and stored in one of the image
memories 8. This image is transferred on a data bus 15,
15 through switches 14 and 31 and into a Reference Image Memory
30. This master image is displayed on a CRT (television)
monitor 32. (Any of the images in the various memories can
be displayed on the monitor 32, but for simplicity, only the
Reference Image Memory 30 is shown connected to the monitor
20 32). The Reference Image Memory is an FB-150 frame buffer
(available from Imaging Technology Inc.). The operator then
selects an area of the image to inspect and the location of
a fiducial by moving outline rectangles displayed over the
image of the master reference. The fiducial is an image
25 area that will be located in subsequent images and used to
align subsequent images to the master reference image. The
selection of the inspection area and fiducial can be also be
automatic, based on information in a data base about the
part to be inspected. A method is described below for
30 automatic selection of the fiducial based on certain quality
measures. The fiducial image area is copied from the

reference image memory 30 into the fiducial image memory 10
by the control computer 100.

Next a series of other known good images are
acquired and averaged into the reference image memory 30.

5   Because these additional images may be shifted in position
with respect to the master image, these additional images
must be aligned or brought into registration with the master
reference image before averaging. The method of aligning or
registering the two images is described below. This same

10 method of alignment is also used during the inspection mode
of operation, so the additional images with unknown
positions are called the "sample" images.

Sample images to be aligned are acquired and stored
in one of the image memories 8. A small patch of the sample

15 image is transferred to the alignment computation block 11
via data bus 15. This image patch is taken from the input
image area where the fiducial is expected to be located, and
is slightly larger than the fiducial. The alignment
procedure has two major steps, described in more detail

20 below. First, the image patch from the sample image is
searched to find the location of the fiducial to within a
fraction of a pixel. The positional difference between the
location of the fiducials in the sample image and in the
reference image indicates the amount of positional shifting

25 required to bring the images into alignment (registration).
Second, the sample image is shifted to align (register) with
the reference image by moving it by the distances computed
in the first step.

The fiducial location computation 11 is illustrated

30 by Fig. 3. In Fig. 3a the patch (202) from the sample image
is shown as an 11 by 11 array of dots. The expected
location of the fiducial in the sample images is at the

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center of this image patch (white dot 204), but positioning
and part variability can cause the true position of the
fiducial to be anywhere in the 7 by 7 area (206) shown as
grey dots. The black dots are border pixels, where a match

5   cannot be found because the reference fiducial pattern would
extend outside the sample image patch. The location of the
fiducial (in the Fig., each pixel of the fiducial is shown
in a small square) in the sample image is found by
correlating the patch of sample image containing the

10 fiducial with the image of the reference fiducial stored in
the fiducial image memory 10.

The reference fiducial is correlated at every
location within the sample image patch where it can fit
(i.e., with the grey dot area). For example, if the

15 reference fiducial is 5 by 5 pixels there are 49 possible
correlation locations (grey dots).

Correlation consists of multiplying the reference
fiducial values with the values in an area of the sample
image patch. In Fig. 3a, a correlation at one location is

20 represented by a 5 by 5 array of square "reference" pixels
surrounding the sample pixels. This represents the
reference image values being multiplied by the sample image
values. These multiplied values are then summed, and a high
value of the sum (i.e., the correlation value) indicates a

25 close match between the reference fiducial pattern and the
pattern of pixel intensities in a sample image area.

The correlation values at the various possible
positions form an array of values, considered to be a
surface, which peaks where the input and reference images

30 are in registration, as shown in Fig. 3b. The sample image
patch must be large enough to contain the fiducial and

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additional borders of pixels equal to 1/2 the size of the
fiducial, or the registration point will not be found.

     The correlation method used is Fishers Correlation,
or normalized grey-scale correlation. If a is the input
5   image and b is the reference image, then the correlation at
each reference image location x',y', $r_{ab}(x',y')$, is given by
equation 1 of Fig. 3d, where the indices i and j range over
the N reference image points and over the N sample image
points offset by x',y' in the sample image patch. For
10 simplicity in writing and reading this and the following
equations single summations signs are often used to
represent double summations, as shown by the double
subscripts, i,j, on the summations.

     The fiducial image memory 10 and alignment
15 computation 11 of Fig. 1 are subsumed in the IPA-150 (image
processing accelerator) hardware. The IPA-150 is a
high-speed, floating-point image processor also available
from Imaging Technology Inc. To increase the computation
speed the square root need not be taken. Instead equation 1
20 is squared so that r_{ab} is really the square of r_{ab}. This
means that negative correlation values are not reported so
when the numerator of equation 1 is less than zero, zero is
returned. Negative correlation values occur when the sample
and reference images are negatives of each other. Since
25 this is unlikely to occur in the small patches chosen, the
loss of negative values causes no problems.

     The peak of the correlation values (surface) occurs
where the input sample image patch and reference fiducial
image best match. Some care must be taken in the choice of
30 fiducials to prevent poor or multiple correlation peaks.
Fig. 3c shows some example of poor fiducial choices. A
fiducial with a single edge or with image components in only

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one or a few directions will generate a "ridge" of
correlation peaks that cannot be used for registration. If
the fiducial consists of a repeating pattern then there will
be peaks at each pattern position and no way to determine
5   which is the correct peak for registration of the images. A
low contrast or noisy image will not generate a clearly
defined peak. Fiducials from areas that have a significant
amount of part-to-part variation will also not work, as the
correlation peaks may vary randomly in height and position.
10 During the construction of the reference image or during
inspection, defects in the sample image may occur in the
area used for the fiducial. In this case, the correlation
peak will be significantly reduced. This condition is
detected and causes the part being inspected to be classed
15 as defective.

In most IC images, a small part of the semiconductor
structure, but not metalized areas or bonding pads, works
well as a fiducial. To improve the quality of the fiducials
chosen, the system can make certain measurements on the
20 correlation surface and use them as a quality score. These
measures are taken on a correlation surface formed by
correlating the reference fiducial over a small patch of the
reference image, equivalent in size to the patch to be
searched in the sample image. These measures include:

25   1. Sharpness of the correlation peak: The height of
the highest peak compared with the next highest correlation
value. Fiducial quality is a function of correlation peak
sharpness.

2. Peak singularity: Is there only one major peak
30 in the correlation image? If there is more than one peak,
the fiducial is rejected.

3. Symmetry and smoothness of the peak. The peak
ideally falls off equally in all directions. This measure
rejects fiducials with "ridges" of correlation and gives
some confidence that the next step of alignment (analytic
5   surface fitting) will work well.

These measures are computed and combined to form a
quality score that is reported to the operator.
Alternatively, the quality score can be used to
automatically find fiducial areas. To do this, a regular
10   array of fiducial areas are chosen from the master reference
image and a quality score is computed for each. The area
with the best quality score is chosen as the fiducial for
this part.

The location of the correlation peak is used to
15   compute the whole pixel position shift between the sample
and reference images. For example, if the center of the
reference fiducial is assigned a value of 0,0 and the best
match of the reference fiducial and sample image patch is
when the reference fiducial is up one pixel and over two
20   pixels to the left (see Fig. 3b), then the input image must
be moved down one pixel and over two pixels to the right to
register with the reference image.

Whole pixel alignment is accomplished by changing
the addressing of the Image Memory 8. The apparent starting
25   location of this memory can be "panned" (moved in x) or
"scrolled" (moved in y) by whole pixel values and the output
is then an image shifted by whatever amount is required.
The required pixel position shifts x,y are transferred from
the alignment computation 11 via 12 to the image memory 8.
30   The actual transfer is through the control computer 100.

If alignment (registration) is performed only to
whole pixel positions, then the two images may not be

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precisely aligned. When the input sample image and the
reference image are compared (by subtracting the two
images), areas of quickly changing intensity, such as edges
will not exactly overlap in the two images and large
5   difference will result. These differences are not defects,
but are false positives (incorrect defects). To reduce the
false positives level it is very important to precisely
align the two images, to within a fraction of a pixel. This
is called sub-pixel alignment.
10   For most sample images, the best registration
location falls in between pixel centers. The correlation
surface becomes flat or rounded as none of the correlation
samples occur at the peak location. To approximate the
location of the peak, an analytic surface is fitted to the
15   surrounding and rounded peak values. In Fig. 3b the
reference fiducial happens to fall on a whole pixel location
in the sample image, producing a sharp peak in the
correlation. In Fig. 4a the sample image has moved so the
correlation peak would be midway between four pixels. The
20   four correlation values surrounding the correlation peak are
approximately equal and lower than the true peak. In Fig.
4b an analytic surface has been fitted to these surrounding
correlation values, and the peak 302 of this surface
approximates the location of the true correlation peak.
25   Correlation peaks can be modeled by an analytic
surface such as an elliptic paraboloid. With additional
terms for offsets in x, y, height, and a cross axis term,
the equation used for modeling is equation 2 of Fig. 3d,
where p(x,y) is the height of the surface. Assuming that
30   exy is small, then this equation defines a surface that is
essentially an elliptic paraboloid. Sections through the
surface normal to the p(x,y) axis appear as ellipses.

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Sections taken normal to the x or y axes appear as parabolas.

This surface is analytically differentiated and set to 0 to find the peak location.

5   Equation (2) is differentiated with respect to x and y, to get equation 3 of Fig. 3d. The peak occurs when these derivatives are 0. Setting these equations (3) to 0 we get two equations in two unknowns (equations 4 of Fig. 3d) which may be solved for the x and y position of the peak. Note

10   that the value a, the offset term, disappears.

A least-squares fit of the correlation surface data is used to generate the coefficients for the analytic surface. In other words, minimize the squared difference between the correlation data points, $r_{ab}(x,y)$, and the

15   analytic surface data points p(x,y) as in expression 5 of Fig. 3d, where the equation (2) has been substituted for p(x,y). In expression 5, i,j replace x,y as they represent a local coordinate system that will be chosen to simplify the equations. The minimum of this function occurs when its

20   derivative is zero. (The analytic surface is suggested in Bookstein, "From Biostereometrics to the Comprehension of Form", NATO Conference on <u>Applications of Human Biostereometrics</u>, SPIE Vol. 166, 1978, and the least squares method for fitting the surface to the correlation data is

25   based on discussion at pp. 44-53 and pp. 133-151 in Lancaster and Salkauskas, <u>Curve and Surface Fitting: An Introduction</u>, Academic Press (London), 1986, both incorporated by reference). Differentiating (5) with respect to a through f, and setting the resulting

30   expressions to zero gives the six equations labeled 6 in Fig. 3e, where the i,j indices in the (double) summations are not shown to make the equations simpler to write and

points are used for the surface fitting data. These data
are indexed using the local coordinate system shown in Fig.
5a. Performing the summations in equations (6) for i and j
with this coordinate system simplifies the six equations to
5   the equations labeled 7 in Fig. 3e.

Solving these equations (7) gives the coefficients
shown at 8 in Fig. 3e.

These equations are implemented by the simple
kernels shown in Fig. 5b. The coefficients for the
10   least-squares fit of the correlation data to the analytic
model are derived by convolving these kernels with the nine
(3 by 3) correlation values surrounding the correlation
peak, and scaling the results by the fractions shown to the
left of each kernel. Note that the order of evaluation of
15   the kernel values may change, depending upon the coordinate
system used. If there are neighboring correlation peaks
with the same values, the peak closer to the center of the
sample image patch is chosen as the center of the
convolutions.

20   The sub-pixel location of the sample fiducial is
computed by substituting the coefficients derived from the
data using equations (8), into equations (4). This gives an
approximation to the true x,y peak that is accurate to a
fraction of a pixel position, typically 1/6 of a pixel
25   position or better.

These fractional x and y values are shown as sx and
sy on lines 13 in Fig. 1. sx and sy are used to compute a
convolution kernel 19 that is then loaded into convolver 20.
This convolver is used to shift the input sample image,
30   still stored in the image memory 8, by a fraction of a pixel
as described below.

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The second part of the alignment (registration) process is moving the sample (or reference) image into alignment with the reference (or sample) image. Moving the image integer pixel distances has been described above, and is a standard method of alignment. To get more precise registration, the fractional pixel distances computed by the above surface fitting are used to move the image by fractional pixel distances. This method is described below.

A properly sampled analog image, where there are no aliased components, can in theory be reconstructed from the sample values by interpolation. Once the signal has been reconstructed from the sample values, it may be resampled. By using shifted (in space) sample points on resampling, a shifted sampled image is produced. Thus, images can be shifted sub-pixel distances by reconstructing and resampling them.

Reconstructing a signal from sample data can be done in many different ways. The general ideas is that some small number of sample points, g_s, are multiplied by weights derived from an interpolation function, $r(x-n)$, and the sum is the value of the reconstructed signal, g_r, at some intermediate sampling point, x. In one dimension, this operation is the convolution shown in the equation labeled 9 in Fig. 3f.

The sinc function (sin(x)/x) is the ideal interpolation function, but is impossible to use in practice as it extends to infinity. A simple approximation of the sinc function is a cubic function, reflected about the y axis (see Fig. 6b). The cubic is limited in extent, is simple to compute, and has no discontinuity at its end points. As described by Park and Schowengerdt, ("Image Reconstruction by Parametric Cubic Convolution", CVGIP, Vol.

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23, pp. 258-272 incorporated herein by reference) the
equations for the cubic reconstruction function are
equations 10 in Fig. 3f. (Cubic convolution has been
described for other applications other than inspection by
5   comparison--see, for example, Yui, United States patent
4,578,812).

        Equations (10) represent a family of cubic curves
that depend upon the parameter k. k is the slope of v(x) at
$|x| = 1$, and can range from 1 to -1. k controls the
10   high-frequency content of the cubic curve with more negative
values accentuating high frequencies. This invention uses
an optimal value of k = -0.5 as a default, but other values
may be selected. The form of the cubic curve with k = -0.5
is shown in Fig. 6b. v(x) is the value of the cubic at x.
15   In one dimension, resampling using a cubic
interpolation function works as follows (see Fig. 7).
Suppose that the image is to be shifted to the right by
amount s, a fraction of a pixel distance. To reconstruct
the image intensity value at this point s, the surrounding
20   pixel values are multiplied by weighting values derived from
the cubic interpolation equation (10) and summed to give the
reconstructed intensity value of the original image function
at the fractional pixel location s. Note that this
reconstruction of the intensity at s is an approximation,
25   due to noise, a non-ideal interpolation function, and
round-off errors in the calculations. These errors are not
significant in practice.

        In this manner, sample pixel values at any desired
locations can be reconstructed from a set of pixels at fixed
30   locations. Note that due to the limited nature of the cubic
interpolation function, at most four pixel values are used,
but the four values chosen can range over five locations, so

- 25 -

the vector of interpolation values, r, includes a fifth value of 0 on one end or the other. When the shift value, s equals 0, then the interpolation function is equal to 1, so the fixed pixel value is returned.

5   This interpolation method for reconstructing and resampling an image signal is independent in the x and y direction. Therefore, a set of interpolation function values for two dimensional reconstruction and resampling are the Cartesian product of the interpolation values for

10   shifting in x and the interpolation values for shifting in y. The Cartesian product $R(i,j) = r_x(i)r_y(j)$, where r_x represents the five interpolation values in the x direction and r_y the five interpolation values in the y direction. In both sets of interpolation values, one or more values will

15   be 0.

          The resulting array of interpolation values $R(i,j)$ is a kernel for two-dimensional convolution. Convolving the image to be shifted with this kernel interpolates the image values and resamples them, such that the output from the

20   convolution represents the reconstructed image intensity values at shifts sx and sy. Thus, the image sampling points (pixel centers) are effectively "moved" distances sx and sy by convolving with cubic interpolation functions, or "bicubic convolution" for short.

25   Returning to Fig. 1, the fractional alignment values sx and sy computed using the analytic curve fitting of the correlational data (described above) are used to compute a "shifting" kernel. This computation 19 is done either in the alignment computation hardware (IPA-150) or on the

30   control computer and the resulting kernel is loaded into the convolver 20.

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Sub-pixel shifting of an image using bicubic convolution requires 16 multiplications, additions, and other operations at each image point. Shifting an image with many thousands of pixels can therefore take a

5   significant amount of time. The Series 150 has hardware that performs convolutions of up to eight by eight kernel elements at very high speeds (CM150-RTC8 also from Imaging Technology Inc.), thus making this alignment and the subsequent mean accumulation or inspection very fast. The

10   output of the convolver 20 is rounded to eight bits of value by using the look-up table (LUT) 19. A LUT is a general "function box" that can map any input value to any output value.

     The two steps described above are a general

15   procedure for aligning (registering) two images, given that an unchanging fiducial can be found in both images. This alignment method is used both in the construction of the reference image, given a master reference image, and in the subsequent inspection of images.

20   Returning to the construction of a reference image, additional sample images are acquired into image memory 8, and then aligned to the master reference image, using the fiducial values stored in the fiducial image memory 10. The whole pixel shifts of the acquired images are accomplished

25   by changing the pan and scroll address values on the image memory and the fractional shifts by sending the image from bus 15 through the convolver 20 where it is reconstructed and resampled. This shifted image is then averaged into the reference image memory.

30   Averaging is done by opening data switch 31 and closing data switch 33. Shifted images are added by the arithmetic-logic unit (ALU-150 also from Imaging Technology

Inc.) 40 with the existing data 34 in the reference image
memory 30, and the sum 41 is put back into the reference
image memory. With N images summed together, the sum image
is divided by N using the ALU 40. Data from the Reference

5   image memory 30 goes through data path 34 into the ALU where
it is divided by N, output on data path 41 and returned to
the reference image memory 30 via data switch 33. The
ALU-150 performs division by shifting, so N is chosen to be
a power of 2. This is not required and other

10 implementations might allow any value for N.

        When the reference image has been computed and
stored in 30, a small patch of this image containing the
image of the fiducial area is transferred by the control
computer 100 into the Fiducial Image Memory 10. This will

15 serve as the reference fiducial for the alignment of images
of inspected parts.

        A "variability" image is constructed in conjunction
with the construction of the reference image. The
variability image specifies the acceptable range of part

20 pattern intensity variation at each point (pixel) in the
image. The disclosed method uses the standard deviation of
pixel intensities at each point in the image to construct
the variability image, but other methods such as using some
fraction of the pixel intensity range at each point could

25 also be used.

        Standard deviation (s.d.) at a given point in the
image is given in equation 11 of Fig. 3f, where z_k are
intensity values across the ensemble of images and M_z are
the mean (average) intensity values across the ensemble of

30 images. Rearranging (11) gives equation 12 of Fig. 3f.

        The mean M_z is the average value accumulated in the
reference image memory. The sum of the squares of z_k (pixel

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intensity values across the ensemble of images) are
accumulated in the variability image memory 53. As aligned
images come from the convolver 20 to be added into the
reference image memory 30, they are also sent to the
5 variance computation 50 via data switch 51.

Initially the variability image memory 53 is all
zeros. As images come into the variance computation 50, the
pixel values are squared and added to the values in the
variability image memory 53 using data buses 52. This
10 accumulates the sum of the pixel values squared for each
image point.

At the end of the formation of the reference image
average, these mean values are transferred via data switch
54 to the variance computation where they are squared and
15 subtracted from the sum of squared pixel values held in
variability image memory 53. These values are divided by N
and the square root is taken to give the standard deviation.

The variability image is then constructed by setting
each pixel in this memory to some multiple plus an offset of
20 the standard deviation at that point. For example, to set a
limit of variability of three standard deviations, the s.d.
values would be multiplied by three. A three standard
deviations limit means that the variation in sample image
intensity at a point must be greater than 99% of the maximum
25 variation normally expected for the point to be declared a
potential defect. The computed and scaled standard
deviation values are stored back into variability image
memory 53 via data buses 52.

The next step in the training mode is to select a
30 shape and size of kernel for the grey-level erosion step.
The grey-level erosion will set the edges of groups of
pixels to zero value. This removes small patches of noise,

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or "ghost" edges due to slight misalignment in the
structures of reference and sample parts. In the
implementation with the Series 150, the erosion is performed
by the CM150-RVF (also from Imaging Technology Inc.), and
5   can have a kernel size of up to eight by eight, meaning that
groups of pixels as large as eight by eight can be removed
(zeroed) from the potential defect image in one pass through
this hardware.

Finally, limits on acceptable defects are selected.
10   The limits selected depend upon the defect analysis 70
selected. For the example analysis described below, the
maximum acceptable number of defect pixels and the value of
the maximum acceptable defect are selected.

The multiple and offset of the standard deviation,
15   the erosion kernel shape and size, and the limits for
defects are usually selected based on comparing the results
of a test run with human visual inspection. To accomplish
this, an IC wafer containing many ICs is inspected and the
parameters of the automated inspection are adjusted to bring
20   the reported defects into agreement with those found by
careful visual inspection by a human of the same wafer.
Typically, a single set of parameters can be used for many
different kinds of ICs manufactured by the same fabrication
process.

25   Once the inspection system has been taught the
reference image, the range of acceptable variations and
etc., the system is put into inspection mode and can inspect
patterned parts at high speeds. A typical inspection cycle
is described below.

30   The Positioner 1 brings the part to be inspected to
within a few pixel positions of a known position under the
camera 3 and with near zero angular rotation. The camera

image is digitized 7 and stored in one of the image memories
8. As described above, the storing of this sample image may
proceed in parallel with the processing of the previously
digitized sample image. A small patch of the sample image

5   is transferred via switch 9 and data bus 15 into the
alignment computation 11. In 11 the location of the
fiducial in the sample image is determined to sub-pixel
location using the method of correlation and analytic curve
fitting described above. The shifts required to bring the

10 sample and reference images into alignment are sent (12) to
the image memory 8 (for whole pixel shifts) and are used to
compute (19) a bicubic convolution kernel. This kernel is
placed in the convolver 20 and is used to align the sample
and reference image to a fraction of a pixel in position.

15   The whole pixel aligned sample image comes from
image memory 8 through data switch 9 and data bus 14 and is
shifted by convolver 20 and rounded to eight bits by LUT 21.
The aligned reference image goes through the data switch 14
and is subtracted on a point-by-point basis from the

20 reference image stored in the reference image memory 30
using the ALU 40. The subtracted image values are sent via
data bus 41 to the absolute value computation 42 where
negative values are turned into the equivalent positive
values. That is, if z is less than 0, then z is replaced

25 with -z (a positive number). In practice, both the
subtraction and the absolute value are performed at high
speed using the ALU-150 hardware. The absolute value is
taken because, in general, sample defects may be brighter or
darker than the reference image.

30   The result of subtracting the sample from the
reference image and taking the absolute value is called the
difference image, and these differences could represent

defects. However, acceptable variations in parts, noise,
and minor misalignments give rise to differences that are
not considered to be defects (false positives). To reduce
these false positive defects the variability image stored in
5   the variability image memory 53 is subtracted using data
paths 43 and 54 by the look-up table 50. The look-up table
is programmed to subtract the variability image values from
the difference image and if the result is less than 0, a 0
is output. This "thresholds" or reduces difference image
10   values, and this threshold depends upon the intrinsic
variability of the ensemble of known good images used to
construct the variability image. The result of this
subtraction thresholding is called the potential defect
image. The look-up table 50 is implemented using a
15   CM150-LUT16 (also from Imaging Technology Inc.).

There can still be false positive defects in the
potential defect image, and so this image is passed via data
bus 59 to the erosion processor 60. The erosion processor
sets small groups of pixels to zero and zeros pixels at the
20   edges of larger groups (blobs) of pixels. The erosion step
is optional and its use and the size of the erosion is
selected during the training procedure. The resulting image
is called the error image, and this image is transferred via
data bus 61 to the Defect Analysis computation 70.

25   The defect analysis is designed to measure the
values and structure of groups of pixels in the error image.
These measures are compared against previously specified
limits for the measure and if some or all of these measures
are outside of the limits, the control computer 100 is
30   notified via data path 71.

The defect analysis computation can take many forms.
Some example measures are the size of the largest grouping

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of pixels (a "blob" of pixels), or the orientation of the longest group of pixels--perhaps indicating a scratch on the IC surface. For illustrative purposes two simple measures are described herein.

5   As pixels in the error image are sent to the defect analysis computation, the number of pixels greater than zero are counted and the maximum value of all of these pixels is remembered. These two values give a measure of the total amount of error "area" (the total number of pixels) and an
10   idea of the magnitude of the error (the largest value of the error image). While quite simple, these measures are sufficient for many IC inspection tasks.

The present invention, by maintaining gray-scale (continuous valued) pixel values throughout the processing,
15   allows a variety of defect measures to be made on the error image, such as the "volume" (x, y area times pixel value) of blobs or groups of pixels. Thus the present invention can be adjusted to provide more sophisticated and sensitive measures of defects as well as to provide better
20   classifications of defects for process control.

If a defect is detected by comparing the measures with previously trained limits, then the measures and an error signal are sent to the control computer. Alternatively, the measures may be sent to the control
25   computer where they are compared against the trained limits. In either case, an error report 101 is issued if the part under inspection has produced defect measures that are greater than the previously specified limits, and the part is then rejected as being defective.
30   If desired, the measures generated by the defect analysis can be accumulated and summarized to provide some indication of the types and magnitude of errors. This

information can be used to adjust the process that produces
the parts. For example, in IC inspection the existence of
larger blobs may indicate that dust and other particulate
matter is contaminating the fabrication process.

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Claims

1   1. A method for determining the amount of
2   misalignment between a digitized sample image of a patterned
3   part and a corresponding digitized reference image,
4   comprising

5   performing a correlation operation on said images to
6   generate a correlation surface indicative of an integral
7   number of pixels by which said images are misaligned, and
8   fitting said correlation surface to an analytic
9   surface to determine a fractional number of pixels by which
10   said images are misaligned.

1   2. The method of claim 1 wherein said analytic
2   surface comprises an elliptic parabaloid-like surface.

1   3. The method of claim 1 or 2 further comprising
2   setting negative correlation values to zero in said
3   correlation operation.

1   4. A method for inspecting a patterned part
2   comprising
3   forming a digitized sample image of said patterned
4   part,
5   performing a convolution operation on said digitized
6   sample image to effectively shift said digitized sample
7   image by a fraction of a pixel relative to a corresponding
8   digitized reference image, and
9   comparing said shifted digitized sample image with
10   said reference image.

1   5.   The method of claim 4 further comprising
2   storing adjacent pixels of said digitized sample
3   image at successive addresses in a memory, and
4   adjusting references to said addresses to
5   effectively shift said digitized sample image by an integer
6   number of pixels relative to a corresponding digitized
7   reference image.

1   6.   The method of claim 4 wherein said convolution
2   operation comprises a bicubic convolution.

1   7.   the method of claim 4 further comprising
2   prior to performing said convolution operation,
3   determining an amount of misalignment between said digitized
4   sample image and said corresponding digitized reference
5   image, comprising
6   performing a correlation operation on said images to
7   generate a correlation surface indicative of an integral
8   number of pixel by which said images are misaligned, and
9   fitting said correlation surface to an analytic
10   surface to determine a fractional number of pixels by which
11   said images are misaligned.

1   8.   A method for automatically adjusting the offset
2   and gain of a digitizer with respect to a signal
3   representing images of patterned parts comprising
4   (a) digitizing an image signal as pixel intensity
5   values using an initial offset value,
6   (b) determining the maximum (max) and minimum (min)
7   of said pixel intensity values,
8   (c) adjusting said initial offset value up or down
9   by a value $F = ((UD-max) - (min-LD))/2$ (where UD and LD are

10 respectively upper and lower decrease thresholds) to obtain

11 an adjusted offset value,

12   (d)   digitizing an image signal as pixel intensity

13 values using said adjusted offset value,

14   (e) repeating step (b)

15   (f) if min is greater than LI, a lower increase

16 threshold and max is less than UI, an upper increase

17 threshold, the gain is increased by an increment; otherwise,

18 if min is less than LD and max is greater than UD, the gain

19 is decreased by a decrement,

20   (g) repeating steps (a) through (f) until neither

21 condition of (f) is true.

1   9.   A method of automatically choosing a fiducial

2 area within a digitized sample image for use in aligning

3 said image with a reference image, comprising

4   selecting multiple possible fiducial areas with said

5 image,

6   forming a correlation surface for each said possible

7 fiducial area by correlating said fiducial area with itself

8 and adjacent portions of said image,

9   generating a measure of the merit of each said

10 possible fiducial area, and

11   comparing said measures to choose said fiducial

12 area.

1   10.   The method of claim 9 wherein said measure

2 comprises at least one of:

3   (a) the sharpness of a peak of said correlation

4 surface,

5   (b) whether or not there is a single peak of said

6 surface,

7   (c) the symmetry and smoothness of said peak.

1   11. The method of claim 1, 4, 8, or 9 wherein said

2 pixels are grey level pixels, each having one of more than
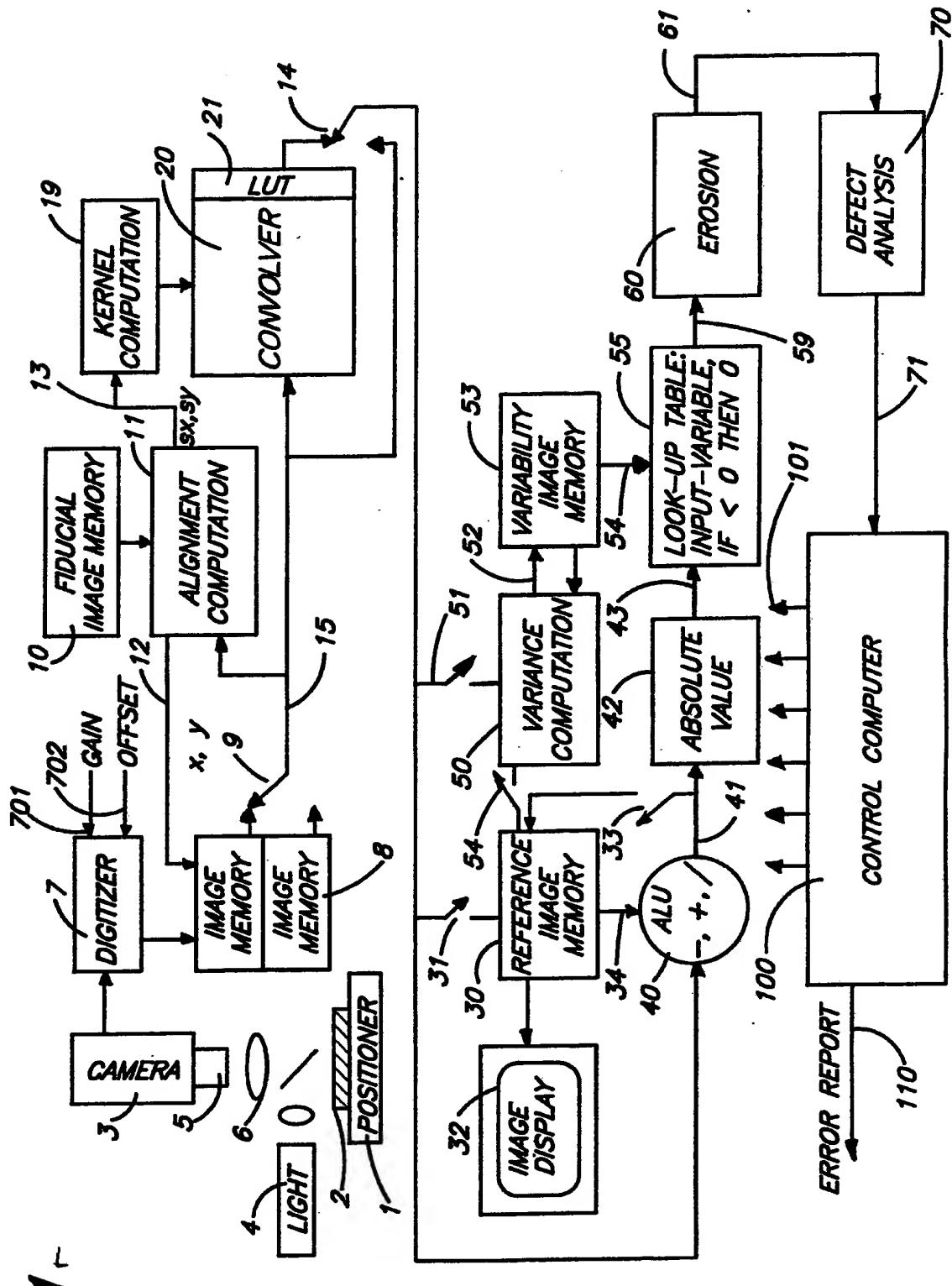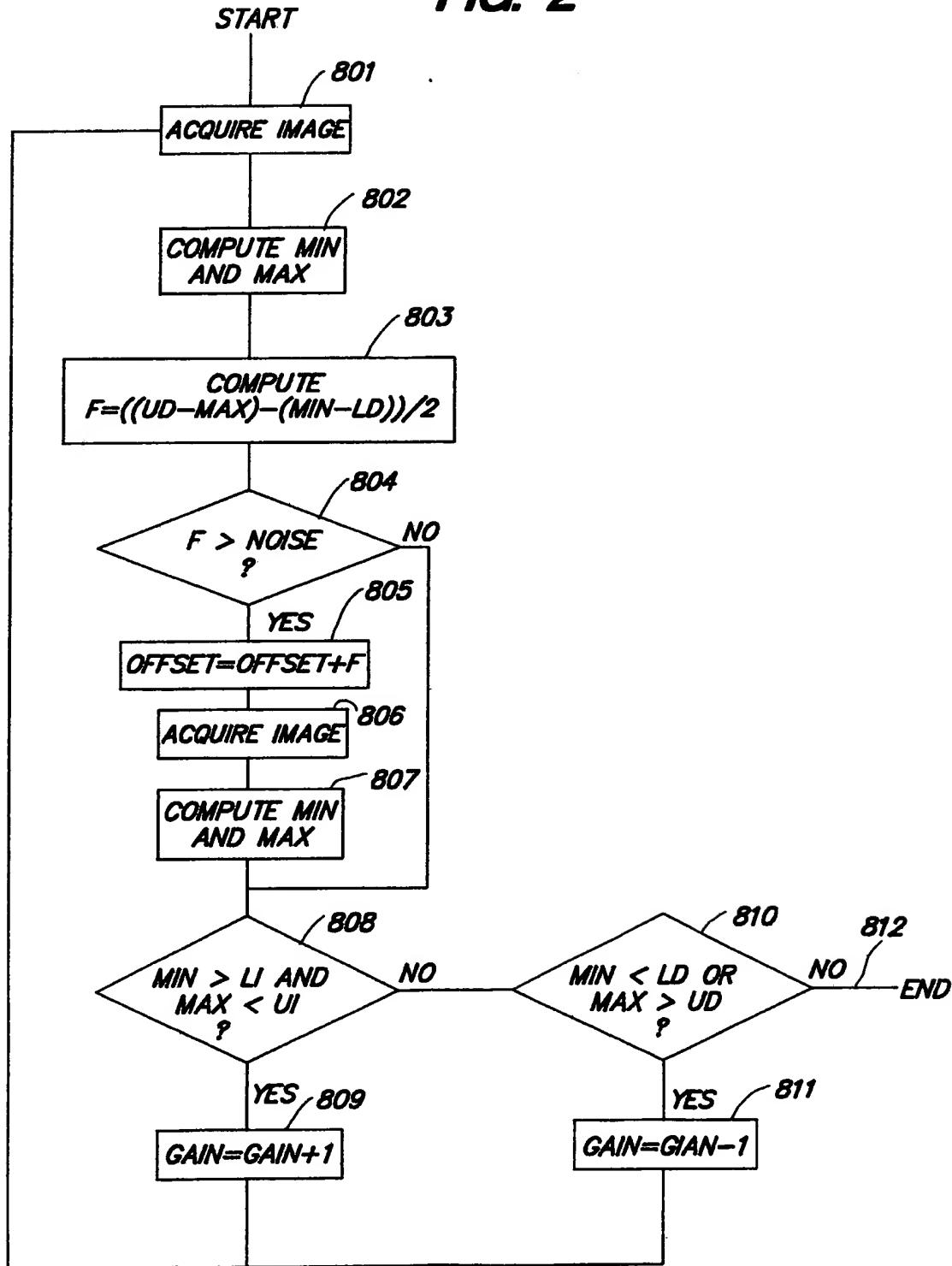
3 two possible values.

1 / 10

FIG. 1

FIG. 2

```
                    START
                      │
                      │      ┌801
                      ▼
              ┌──────────────────┐
         ┌───▶│  ACQUIRE IMAGE   │
         │    └──────────────────┘
         │             │
         │             │      ┌802
         │             ▼
         │    ┌──────────────────┐
         │    │   COMPUTE MIN    │
         │    │     AND MAX      │
         │    └──────────────────┘
         │             │
         │             │              ┌803
         │             ▼
         │  ┌──────────────────────────┐
         │  │         COMPUTE          │
         │  │  F=((UD−MAX)−(MIN−LD))/2  │
         │  └──────────────────────────┘
         │             │
         │             │        ┌804
         │             ▼
         │         ╱───────╲        NO
         │        ╱ F > NOISE╲──────────────┐
         │        ╲    ?     ╱               │
         │         ╲───────╱                 │
         │             │                     │
         │          YES│    ┌805             │
         │             ▼                     │
         │    ┌──────────────────┐           │
         │    │ OFFSET=OFFSET+F  │           │
         │    └──────────────────┘           │
         │             │       ┌806          │
         │             ▼                     │
         │    ┌──────────────────┐           │
         │    │  ACQUIRE IMAGE   │           │
         │    └──────────────────┘           │
         │             │       ┌807          │
         │             ▼                     │
         │    ┌──────────────────┐           │
         │    │   COMPUTE MIN    │           │
         │    │     AND MAX      │           │
         │    └──────────────────┘           │
         │             │                     │
         │             ▼◀────────────────────┘
         │         ┌808                          ┌810              ┌812
         │      ╱────────╲      NO        ╱────────────╲     NO
         │     ╱ MIN > LI  ╲──────────▶ ╱  MIN < LD OR  ╲──────────── END
         │     ╲  AND       ╱           ╲   MAX > UD    ╱
         │      ╲ MAX < UI ╱             ╲      ?      ╱
         │       ╲   ?   ╱                ╲──────────╱
         │        ╲────╱                      │
         │          │                     YES │   ┌811
         │       YES│  ┌809                    ▼
         │          ▼                  ┌──────────────┐
         │  ┌──────────────┐           │ GAIN=GIAN−1  │
         │  │ GAIN=GAIN+1  │           └──────────────┘
         │  └──────────────┘                  │
         │          │                         │
         └──────────┴─────────────────────────┘
```
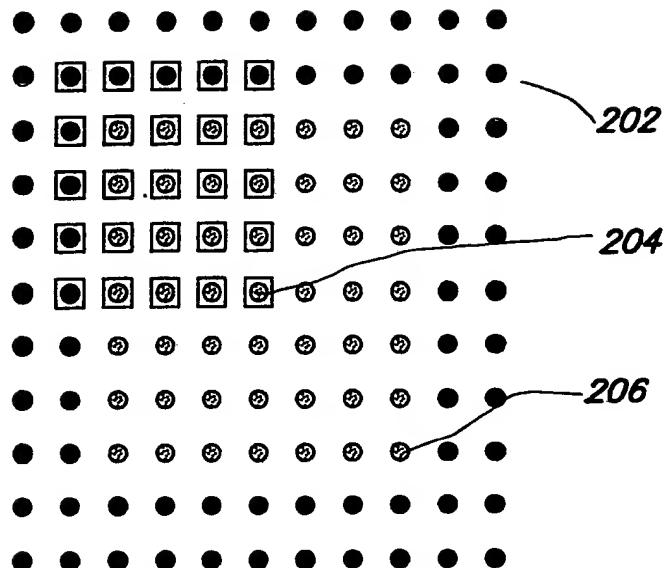
FIG. 3a

FIG. 3b
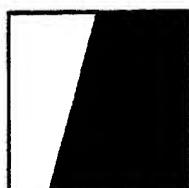
SINGLE   PATTERN   NOISY
EDGE   REPEATS   PATTERN
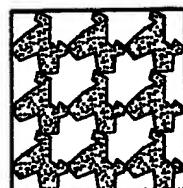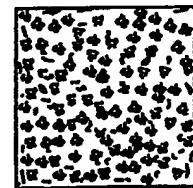
FIG. 3c

FIG. 3d-1

$$r_{ab}(x',y') = \frac{N\sum_{i,j}^{N} a_{i+x',j+y}\, b_{i,j} - \left(\sum_{i,j}^{N} a_{i+x',j+y'}\right)\left(\sum_{i,j}^{N} b_{i,j}\right)}{\sqrt{\left(N\sum_{i,j}^{N} a_{i+x',j+y'}^{2} - \left(\sum_{i,j}^{N} a_{i+x',j+y'}^{2}\right)^{2}\right)\left(N\sum_{i,j}^{N} b_{i,j} - \left(\sum_{i,j}^{N} b_{i,j}\right)^{2}\right)}}$$

FIG. 3d-2

$$p(x,y) = a + bx + cy + dx^2 + exy + fy^2$$

FIG. 3d-3

$$\frac{\delta p}{\delta x} = b + 2dx + ey, \qquad \frac{\delta p}{\delta y} = c + ex + 2fy$$

FIG. 3d-4

$$x = \frac{ec - 2bf}{4df - e^2}, \qquad y = \frac{be - 2cd}{4df - e^2}$$

FIG. 3d-5

$$\min\left[\sum_{i,j}\left(r_{ij} - (a + bi + cj + di^2 + eij + fj^2)\right)^2\right]$$

FIG. 3e-6

$$\sum r_{ij} = a\sum 1 + b\sum i + c\sum j + d\sum i^2 + e\sum ij + f\sum j^2$$

$$\sum r_{ij}\, i = a\sum i + b\sum i^2 + c\sum ij + d\sum i^3 + e\sum i^2 j + f\sum ij^2$$

$$\sum r_{ij}\, j = a\sum j + b\sum ij + c\sum j^2 + d\sum i^2 j + e\sum ij^2 + f\sum j^3$$

$$\sum r_{ij}\, i^2 = a\sum i^2 + b\sum i^3 + c\sum i^2 j + d\sum i^4 j + e\sum i^3 j + f\sum i^2 j^2$$

$$\sum r_{ij}\, i\, j = a\sum ij + b\sum i^2 j + c\sum ij^2 + d\sum i^3 j + e\sum i^2 j^2 + f\sum ij^3$$

$$\sum r_{ij}\, j^2 = a\sum j^2 + b\sum ij^2 + c\sum j^3 + d\sum i^2 j^2 + e\sum ij^3 + f\sum j^4$$

FIG. 3e-7

$$\sum r_{ij} = 9a + 6b + 6f$$

$$\sum r_{ij}\, i = 6b$$

$$\sum r_{ij}\, j = 6c$$

$$\sum r_{ij}\, i^2 = 6a + 6d + 4f$$

$$\sum r_{ij}\, i\, j = 4e$$

$$\sum r_{ij}\, j^2 = 6a + 4d + 6f$$

FIG. 3e-8

$$b = \frac{1}{6}\sum_{i,j} r_{ij}\, i$$

$$c = \frac{1}{6}\sum_{i,j} r_{ij}\, j$$

$$d = \frac{1}{6}\sum_{i,j} r_{ij}\, [3i^2 - 2]$$

$$e = \frac{1}{4}\sum_{i,j} r_{ij}\, i\, j$$

$$f = \frac{1}{6}\sum_{i,j} r_{ij}\, [3j^2 - 2]$$

FIG. 3f-9

$$g_r(x) = \sum_{n_{ab}=-\infty}^{\infty} g_s(n)r(x-n)$$

FIG. 3f-10

$$v(x) = (k+2)|x|^3 - (k+3)x^2 + 1, \quad \text{for } |x| < 1$$

$$v(x) = k|x|^3 + 5kx^2 - 4k, \qquad \text{for } 1 \le |x| \le 2$$

$$V(X) = 0, \quad \text{otherwise.}$$

FIG. 3f-11

$$\text{s.d.}(x,y) = \sqrt{\frac{\sum_{k}^{N}(z_k - M_z)^2}{N}} \qquad M_z = \frac{\sum_{k}^{N} z_k}{N}$$

FIG. 3f-12
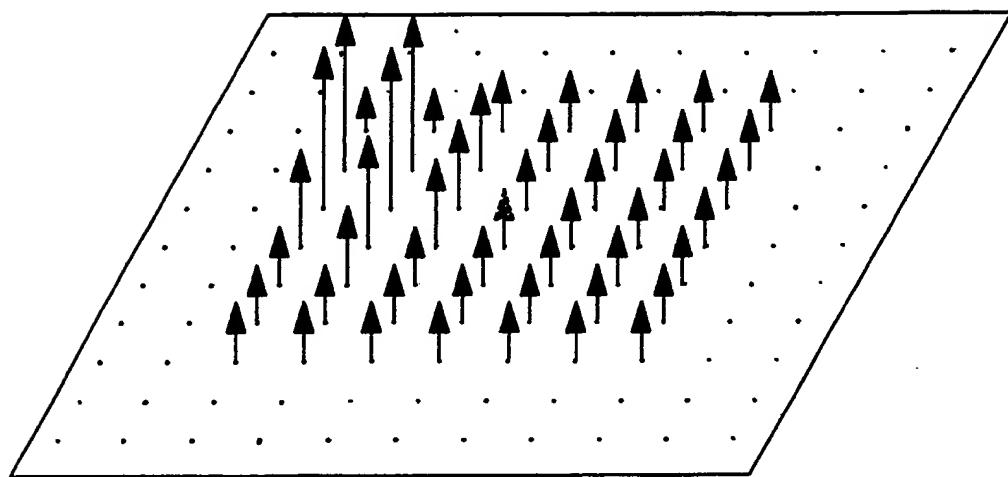
$$\text{s.d.}(x,y) = \sqrt{\frac{\sum_{k}^{N} z_k^2 - M_z^2}{N}}$$
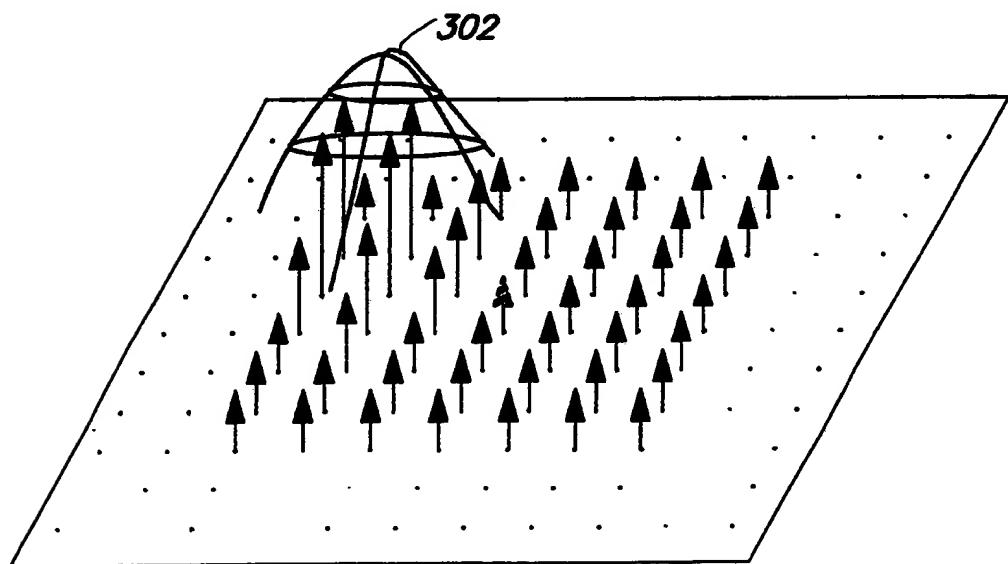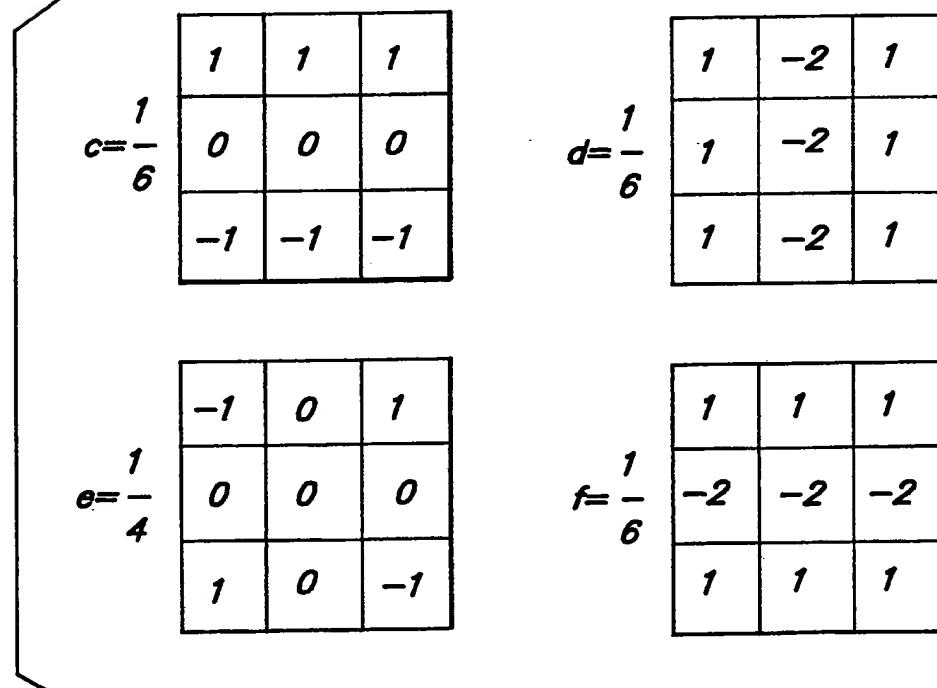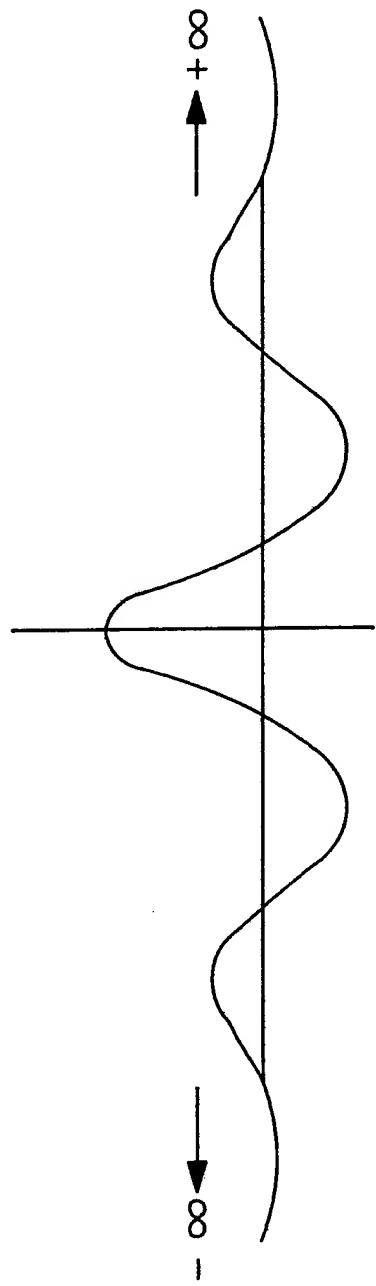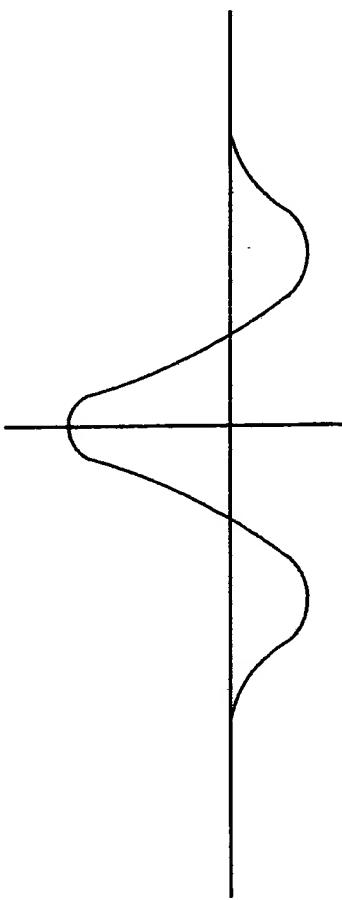
FIG. 4a
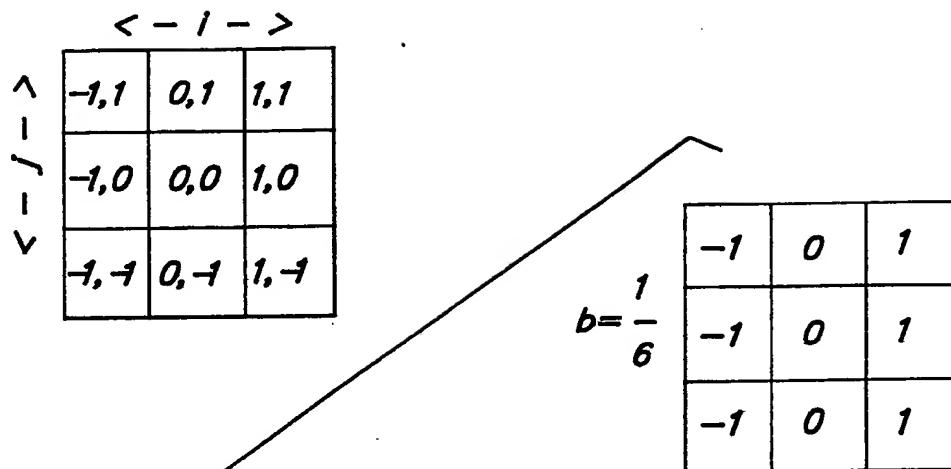

FIG. 4b

FIG. 5a

$< - i - >$

-1,1	0,1	1,1
-1,0	0,0	1,0
-1,-1	0,-1	1,-1

$b=\dfrac{1}{6}$

-1	0	1
-1	0	1
-1	0	1

$c=\dfrac{1}{6}$

1	1	1
0	0	0
-1	-1	-1

$d=\dfrac{1}{6}$

1	-2	1
1	-2	1
1	-2	1

$e=\dfrac{1}{4}$

-1	0	1
0	0	0
1	0	-1

$f=\dfrac{1}{6}$

1	1	1
-2	-2	-2
1	1	1

FIG. 5b

FIG. 6a

FIG. 6b
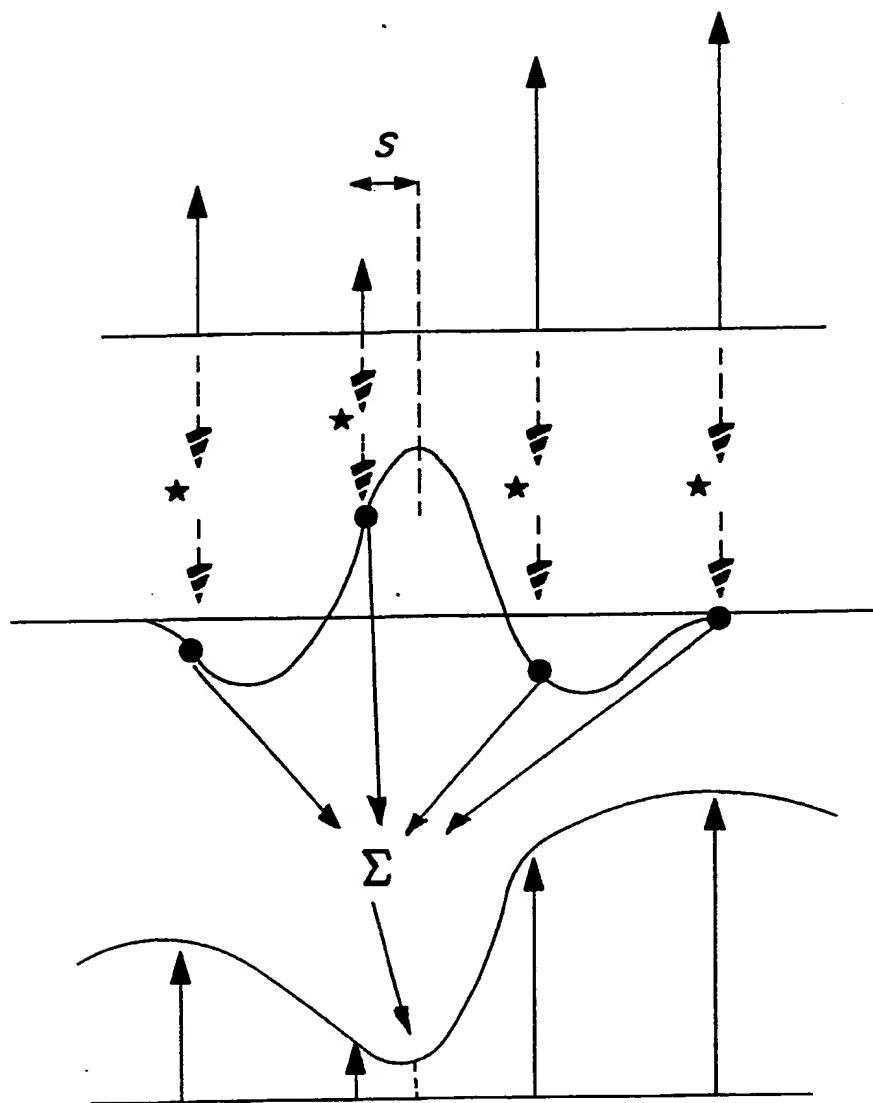
FIG. 7

INTERNATIONAL SEARCH REPORT

I. CLASSIFICATION OF SUBJECT MATTER (if several classification symbols apply, indicate all) 6

According to International Patent Classification (IPC) or to both National Classification and IPC

IPC (5): G06K 9/00
U.S.Cl.: 382/8

II. FIELDS SEARCHED

Minimum Documentation Searched 7	
Classification System	Classification Symbols
U.S.	382/18, 42, 44, 45, 50, 53

Documentation Searched other than Minimum Documentation
to the Extent that such Documents are Included in the Fields Searched 8

III. DOCUMENTS CONSIDERED TO BE RELEVANT 9

Category *	Citation of Document, 11 with indication, where appropriate, of the relevant passages 12	Relevant to Claim No. 13
X	US, A, 4,805,123 (SPECHT ET AL.) 14 February 1989 See column 6, lines 15-62, col. 8, lines 26-44 and column 5, lines 16-21.	1-2, 4,7 and 11/1,11/4
X,P	US, A, 4,963,036 (DRISKO ET AL.) 16 October 1990 See Figures 5-7 and 9 and refer to column 3, line 51 through column 7, line 41.	8 and 11/8
X	US, A, 4,794,648 (AYATA ET AL.) 27 December 1988 See Figures 1-5 and refer to column 3, line 10 through column 7, line 43.	9-11
Y	US, A, 4,613,857 (WALKER) 23 September 1986 See Figure 1 and abstract.	5
Y	US, A, 4,578,812 (YUI) 25 March 1986 See column 1, lines 30-48 and column 9, lines 22-31.	6

* Special categories of cited documents: 10

"A" document defining the general state of the art which is not considered to be of particular relevance

"E" earlier document but published on or after the international filing date

"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)

"O" document referring to an oral disclosure, use, exhibition or other means

"P" document published prior to the international filing date but later than the priority date claimed

"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step

"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art.

"&" document member of the same patent family

IV. CERTIFICATION

Date of the Actual Completion of the International Search	Date of Mailing of this International Search Report
02 October 1991	24 OCT 1991
International Searching Authority	Signature of Authorized Officer NGUYEN NGOC-HO
ISA/US	INTERNATIONAL DIVISION Barry Stellrecht

FURTHER INFORMATION CONTINUED FROM THE SECOND SHEET

V. ☐ OBSERVATIONS WHERE CERTAIN CLAIMS WERE FOUND UNSEARCHABLE [1]

This international search report has not been established in respect of certain claims under Article 17(2) (a) for the following reasons:

1. ☐ Claim numbers   , because they relate to subject matter [12] not required to be searched by this Authority, namely:

2. ☐ Claim numbers ... , because they relate to parts of the international application that do not comply with the prescribed requirements to such an extent that no meaningful international search can be carried out [13], specifically:

3. ☐ Claim numbers_____, because they are dependent claims not drafted in accordance with the second and third sentences of PCT Rule 6.4(a).

VI. ☒ OBSERVATIONS WHERE UNITY OF INVENTION IS LACKING [2]

This International Searching Authority found multiple inventions in this international application as follows:

<div align="center">See Attached Sheet</div>

1. ☒ As all required additional search fees were timely paid by the applicant, this international search report covers all searchable claims of the international application.

2. ☐ As only some of the required additional search fees were timely paid by the applicant, this international search report covers only those claims of the international application for which fees were paid, specifically claims:

3. ☐ No required additional search fees were timely paid by the applicant. Consequently, this international search report is restricted to the invention first mentioned in the claims; it is covered by claim numbers:

4. ☐ As all searchable claims could be searched without effort justifying an additional fee, the International Searching Authority did not invite payment of any additional fee.

Remark on Protest

☐ The additional search fees were accompanied by applicant's protest.

☒ No protest accompanied the payment of additional search fees.

Form PCT/ISA/210 (supplemental sheet (2) (Rev. 11-87)

continuation of Form PCT/ISA/210

I. Claims 1-7, 11/1 and 11/4 drawn to a method for performing correlation and convolution classified in 382/44.

II. Claims 8 and 11/8 drawn to method for adjusting the offset and gain of a digitizer classified in 382/50.

III. Claims 9, 10 and 11/9 drawn to a method for choosing a fiducial area by correlation classified in 382/42.